

CHANDRA DETECTS INVERSE COMPTON EMISSION FROM THE RADIO GALAXY 3C 219

G. Brunetti¹, A. Comastri², D. Dallacasa³, M. Bondi¹, M. Pedani⁴, and G. Setti³¹Istituto di Radioastronomia del CNR, via P.Gobetti 101, I-40129 Bologna, Italy²INAF, Osservatorio Astronomico di Bologna, via Ranzani 1, I-40127 Bologna, Italy³Dipartimento di Astronomia, Universita' di Bologna, via Ranzani 1, I-40127 Bologna, Italy⁴Centro Galileo Galilei - S/C La Palma, 38700 TF Spain

ABSTRACT

We report the results from a *Chandra* observation of the powerful nearby ($z=0.1744$) radio galaxy 3C 219. We find evidence for non-thermal X-ray emission from the radio lobes which fits fairly well with a combination of IC scattering of CMB and of nuclear photons. The comparison between radio synchrotron and IC fluxes yields a magnetic field strength significantly lower (~ 3) than that calculated under minimum energy conditions; the majority of the energetics is then associated to the relativistic particles.

Key words: Radiation mechanisms: non-thermal – Galaxies: active – Galaxies: individual: 3C 219 – Radio continuum: galaxies – X-rays: galaxies

1. INTRODUCTION

A full understanding of the energetics and energy distribution of relativistic particles in jets and lobes of radio galaxies and quasars is of basic importance for a complete description of the physics and time evolution of these sources. It is assumed that the relativistic electrons originated in the nuclear regions of powerful radio sources, are channeled into the jet and re-accelerated in the radio hot spots, which mark the location of strong planar shocks formed at the beam head of a supersonic jet (e.g. Begelman, Blandford, Rees, 1984) and then diffuse in the radio lobes.

Extended non-thermal X-ray emission from the lobes of radio galaxies and quasars is produced by IC scattering of Cosmic Microwave Background (CMB) photons (e.g. Harris & Grindlay 1979), and/or nuclear photons (Brunetti, Setti & Comastri 1997). In the first case one is sampling the relativistic electrons with Lorentz factor $\gamma \gtrsim 10^3$, while the X-rays from IC scattering of the nuclear far-IR/optical photons are mainly powered by $\gamma = 100 - 300$ electrons whose synchrotron emission typically falls in the undetected hundred kHz frequency range. As a consequence the study of the diffuse X-ray emission from the radio lobes is a unique tool to constrain the spectrum of the relativistic electrons and hopefully the acceleration mechanisms at work.

Non-thermal X-ray emission from the radio lobes has been discovered by **ROSAT** and **ASCA** in a few nearby radio galaxies, namely Fornax A (Feigelson et al. 1995; Kaneda et al. 1995; Tashiro et al. 2001), Cen B (Tashiro et al. 1998), 3C 219 (Brunetti et al. 1999) and NGC 612 (Tashiro et al. 2000). By combining X-ray, as IC scattering of CMB photons, and synchrotron radio flux densities it has been possible to derive magnetic field strengths lower, but within a factor ~ 3 of the equipartition fields. In general, these observations have been complicated due to the weak X-ray brightness, relatively low count statistics and insufficient angular resolution of the instruments.

The enhanced capabilities of the *Chandra* X-ray observatory make now possible to image (on arcsec scale) the radio lobes of powerful radio galaxies and quasars and to disentangle the non-thermal emission from the thermal component (if any) and from the nuclear component. Non-thermal emission from the radio lobes of relatively compact and powerful objects has been successfully detected with *Chandra* in the case of the radio galaxy 3C 295 (Brunetti et al., 2001) and, more recently, in the counter lobes of the radio loud quasars 3C 207 (Brunetti et al. 2002) and 3C 179 (Sambruna et al. 2002). These observations are well interpreted as IC scattering of IR photons from the corresponding nuclear source, thus providing a clear evidence for the presence of low energy electrons ($\gamma \sim 100$) in the radio volumes.

In this paper we report on the *Chandra* observation of the nearby powerful radio galaxy 3C 219. Combined **ROSAT PSPC**, **HRI** and **ASCA** observations have previously found evidence for extended non-thermal emission. This emission has been interpreted as IC scattering of CMB and of IR nuclear photons with the resulting averaged magnetic field intensity in the radio lobes being a factor of ~ 3 below the equipartition value (Brunetti et al. 1999). However, the presence of a bright point-like nuclear source, smearing the diffuse emission in the **ROSAT HRI** image within ~ 15 arcsec distance from the nucleus, and the impossibility to perform spatially resolved spectroscopy with the past satellites has required a follow up observation with *Chandra* to better image the extended emission and to confirm its non-thermal origin. We show that the *Chandra* observation essentially confirms the previous findings. A more detailed discussion of the results will be presented

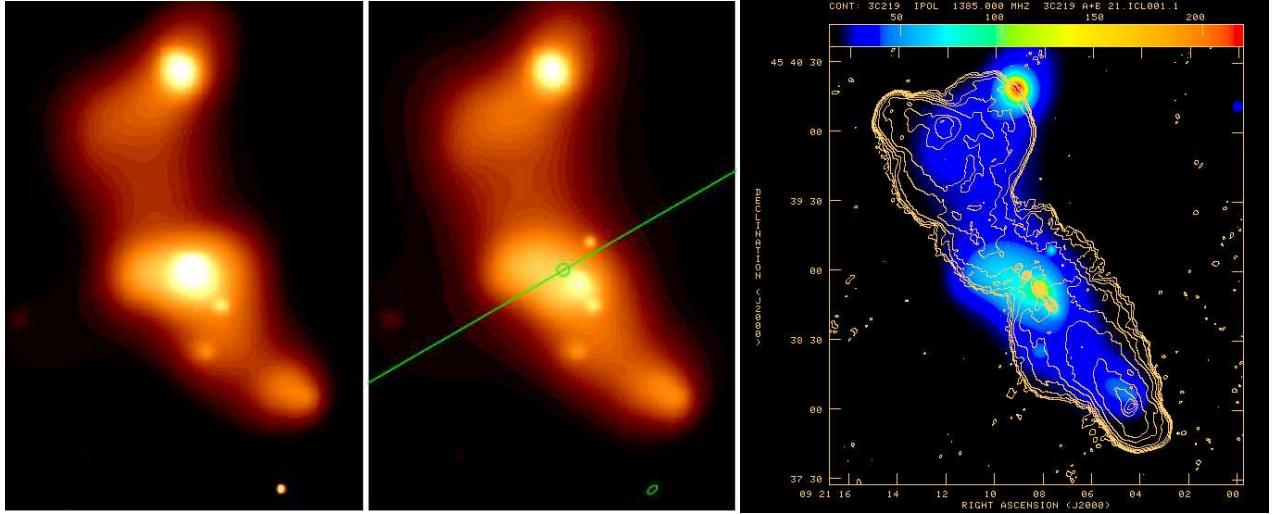


Figure 1. **Panel a)**: 0.3–7 keV smoothed *Chandra* image; **Panel b)**: 0.3–7 keV image smoothed after subtraction of the nucleus and of the pile up streaks; the intensity scales in panel a) and b) are slightly different. In the subtracted image are also visible the X-ray counterparts of the inner knot of the radio jet (panel c) and of the nucleus of the radio galaxy baby-3C 219 (revealed in the high resolution radio images, e.g. Perley et al. 1980). The position of the nucleus of 3C 219 and the pile up direction are reported in the panel; **Panel c)**: VLA 1.4 GHz radio contours superimposed on the *Chandra* image of the panel b).

in a forthcoming paper. $H_0 = 50$ km/s/Mpc and $q_0 = 0.5$ are used throughout.

2. TARGET AND DATA ANALYSIS

3C 219 is a nearby ($z=0.1744$) powerful radio galaxy identified with a cD galaxy of magnitude $M_V=-21.4$ (Taylor et al. 1996), belonging to a non Abell cluster (Burbidge & Crowne 1979). The radio structure is well studied (Perley et al. 1980, Bridle et al. 1986, Clarke et al. 1992): it is a classical double-lobed FRII radio galaxy that spreads over $\sim 180''$ on the sky plane corresponding to a projected size of ~ 690 kpc.

In order to improve the available radio information, to image the radio lobes down to very low brightness and to derive radio spectral index maps, we obtained and analyzed 12 hrs of new observations with the VLA at 1.4 and 5 GHz in C and D configuration and combined them with the observations available in the archive; a deep 1.4 GHz VLA image is reported in Fig.1c (Dallacasa et al., in preparation).

2.1. CHANDRA DATA

The target was observed with the *Chandra* X-ray observatory on 2000 October 11th for about 20 ksec. Although only half of the chip was used in the window mode the nuclear source is significantly affected by pileup and is not considered any further. The raw level 1 data were re-processed using the latest version (CIAO2.2) of the CX-

CDS software. The target was placed about $40''$ from the nominal aimpoint of the back illuminated ACIS S3 chip. There is evidence of an increased background count rate towards the end of the observation. The corresponding time intervals were filtered out leaving about 16.8 ksec of useful data which were used in the spectral and imaging analysis described below. Given that we are interested in the study of the origin of the faint diffuse emission from the radio lobes the background subtraction is an important issue. The particle background can be reduced significantly in the observations carried out in the Very Faint Mode (Vikhlinin 2001). We have employed this technique with the recommended choice of parameters. As a result the quiescent background is reduced up to 30%. Fig.1a–c show several features: relatively faint diffuse emission coincident with the radio lobes showing a brightness increment in the innermost part of the northern lobe and in the region of the back flow of the southern hot spot, a bright clump at north west on the boundary of the northern radio lobe, and two distinct knots at 10–30 arcsec south of the nucleus. These X-ray knots are spatially coincident with the two radio knots of the main jet; the knots and the nuclear properties are not discussed in this contribution.

X-ray spectra have been extracted using appropriate response and effective area functions taking into account the source extension and weighting the detector response and effective area according to the source spectrum.

2.2. THE BACKGROUND CLUSTER

The spectrum of the north west clump is well fitted by a thermal model with a relatively low temperature, $kT \sim 2$ keV (Fig.2). The derived absorbing column density (with a best fit value of $N_H \sim 10^{21} \text{ cm}^{-2}$) is marginally consistent at the 1% confidence level with the Galactic value but we note that the count statistics is rather poor.

A R-band HST observation taken from the archive shows the presence of an excess of optical galaxies at the position of the north west clump, possibly indicating the presence of a cluster/group. We have obtained the spectrum of the most luminous galaxy of the group with the 3.5mt. Telescopio Nazionale Galileo at La Palma (TNG) and identify it with an elliptical galaxy at a redshift $z=0.389$. If we assume that this is the CD galaxy of the group/cluster which emits the observed X-rays, the derived 0.1–10 keV luminosity is $\sim 2 \times 10^{43} \text{ erg/s}$ which is only a factor of ~ 2 below the best fit luminosity expected from a 2 keV temperature cluster by adopting the Luminosity–Temperature relationship of Arnaud & Evrard (1999). Thus we identify the X-ray clump as emission from a background cluster/group at $z = 0.389$.

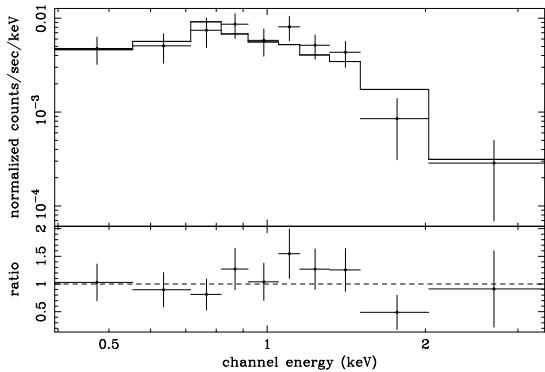


Figure 2. The 0.4–3 keV spectrum extracted from the cluster region is shown compared with a thermal model with $kT=2$ keV, 0.3 solar abundances and $N_H = 8 \times 10^{20} \text{ cm}^{-2}$.

2.3. THE NON-THERMAL EMISSION

The morphology and scale of the faint diffuse X-ray emission is very similar to that of the radio lobes thus suggesting a non-thermal origin. X-ray emission from IC scattering of nuclear photons would outweigh that from IC scattering of CMB at a distance from the nucleus :

$$R_{\text{kpc}} < 70 \times L_{46} (1 - \mu)^2 (1 + z)^{-2} \quad (1)$$

where L_{46} is the isotropic nuclear luminosity in units of 10^{46} erg/s in the far-IR to optical band and μ is the cosine of the angle between the direction of the nuclear seed photons and the scattered photons (roughly speaking the

angle between radio axis and line of sight with μ negative for the far lobe and positive for the near one).

Since we detect diffuse X-ray emission coincident with the radio lobes out to a distance of ~ 300 kpc from the nucleus with a roughly constant brightness (Fig.1), we conclude that the IC scattering of CMB photons is the process which accounts for the majority of the observed X-rays. On the other hand, we notice the presence of a net increment of the X-ray brightness in the innermost ~ 18 arcsec (projected size ~ 70 kpc) of the northern lobe (i.e., the far/counter lobe). If this is of IC origin, as suggested by the fact that the X-rays are strictly related to the morphology of the radio contours (Fig.1c), it should require an additional source of seed photons, most likely from the nucleus (under the reasonable assumption that the density of the relativistic electrons does not significantly increase inward). By imposing an equal contribution to the X-ray flux from the IC scattering of CMB and nuclear photons at a projected distance of ~ 18 arcsec in the northern lobe, and by assuming an angle between the radio axis and the plane of the sky of 20–30°, Eq.(1) yields a far-IR to optical luminosity of the hidden quasar of $\sim 5 \times 10^{45} \text{ erg/s}$ which, indeed, is only a factor ~ 2 lower than that independently estimated by Brunetti et al.(1999) making use of a quasar SED normalized to the nuclear X-ray flux. We stress that the present estimate does not depend on the energy densities of the electrons and of the magnetic field in the radio lobes.

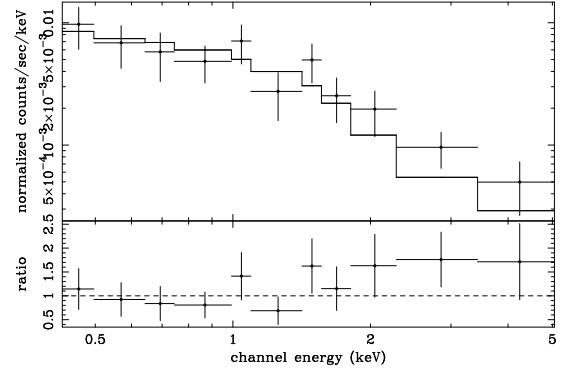


Figure 3. The 0.4–5 keV spectrum extracted from the southern lobe is shown compared with a power law model with the same slope ($\alpha = 0.7$) of the radio spectrum. Despite the relatively poor statistics the excess of the data with respect to the model at $\geq 2 \text{ keV}$ may indicate that the X-ray spectrum is slightly flatter than the radio one.

We performed spectral analysis of the diffuse emission extracting the spectrum from the southern radio lobe which has a better statistics (i.e. the highest ratio between source and background counts). A power law, with the absorption fixed at the Galactic value, does provide

an acceptable description of the data (Fig.3) with the derived X-ray spectral index in the range 0.3 ± 0.4 flatter, but consistent (90% confidence level), with the spectral index derived from the integrated synchrotron spectrum of the radio galaxy ($\alpha = 0.7 - 0.8$; e.g., Laing et al. 1983).

A slightly worse, but still statistically good description of the data, is obtained using a thermal model with abundances fixed at 0.3 solar. It is important to point out that although the quality of the data is not such to discriminate between the two options (power-law and thermal) the derived best fit temperature is ~ 20 keV ($kT > 5.5$ keV at 90% conf. level for one relevant parameter) and thus it appears to be in contrast with the relatively low X-ray luminosity of the diffuse emission. Indeed, from the luminosity-temperature correlation (e.g., Arnaud & Evrard 1999) one has that thermal emission from a hot cluster (with $kT > 6$ keV) would provide a luminosity $\geq 10^{45}$ erg s $^{-1}$, whereas we find that the 0.5–8 keV luminosity of the southern lobe is only $\sim 10^{43}$ erg s $^{-1}$, more than about two orders of magnitude lower than that of a cluster with the same temperature. Due to the large area covered by the faint diffuse emission, we have carefully evaluated the influence of background subtraction on the derived spectral parameters using different extraction regions over the detector. In all the cases the lower limit on the thermal model temperature turns out to be of about 6 keV.

By assuming a power law spectral index $\alpha = 0.7$, consistent with both the X-ray and radio spectra, from the measured synchrotron and IC fluxes extracted from the southern lobe, we derive a magnetic field $B \simeq 2.8 \mu\text{G}$ which is a factor of 3 below the minimum energy field derived with equipartition formulae based on a low energy cut-off in the electron spectrum (Brunetti et al. 1997, assuming $\gamma_{\text{low}} = 50$) or a factor of 2.2 below the equipartition field calculated with the standard equipartition formulae (e.g., Packolczyk 1970). As a consequence, the electron energy density in the southern radio lobe is ~ 60 times that of the average magnetic field. A similar result (but of course less robust) was previously obtained from the combined ROSAT and ASCA study of 3C 219 (Brunetti et al. 1999).

3. CONCLUSION

The relatively short (16.8 ksec) *Chandra* observation of the radio galaxy 3C 219 has successfully detected diffuse X-ray emission from the radio lobes and X-ray emission associated to the main radio jet. The morphology, extension and spectrum of the diffuse emission strongly support a non-thermal origin, most likely IC scattering of CMB photons. In addition the net brightness increment observed in the innermost ~ 70 kpc of the northern radio lobe (the far lobe) suggests an additional contribution from IC scattering of nuclear photons for a reasonable far-IR to optical isotropic luminosity of the hidden quasar of $\sim 5 \times 10^{45}$ erg/s.

By comparing the radio synchrotron and IC/CMB X-ray fluxes from the southern radio lobe we obtain a magnetic field strength approximately a factor ~ 3 lower than the equipartition value.

Additional data from a deeper *Chandra* observation would allow to perform detailed, spatially resolved X-ray spectroscopy of the diffuse emission and to compute B -field intensity map/structure in the radio lobes if combined with the available radio data.

Finally, the relatively bright X-ray clump at north west on the border of the northern radio lobe (Fig.1) is well fitted by thermal emission from a relatively cold plasma (~ 2 keV) in a cluster/group of galaxies at a redshift $z = 0.389$.

REFERENCES

Arnaud, M., Evrard, A.E., 1999, MNRAS, 305, 631
 Begelman, M.C., Blandford, R., Rees, M.J., 1984, Rev. Mod. Phys., 56, 255
 Bridle, A.H., Perley, R.A., Henriksen, R.N., 1986, AJ, 92, 534
 Brunetti, G., Setti, G., Comastri, A., 1997, A&A, 325, 898
 Brunetti, G., Comastri, A., Setti, G., Feretti, L., 1999, A&A, 342, 57
 Brunetti, G., Cappi, M., Setti, G., Feretti, L., Harris, D.E., 2001, A&A, 372, 755
 Brunetti, G., Bondi, M., Comastri, A., Setti, G., 2002, A&A, 381, 795
 Burbidge, G., Crowne, A.H., 1979, ApJS, 40, 583
 Clarke, D.A., Bridle, A.H., Burns, J.O., Perley, R.A., Norman M.L., 1992, ApJ, 385, 173
 Feigelson, E.D., Laurent-Muehleisen, S.A., Kollgaard, R.I., Fomalont, E.B., 1995, ApJ, 449, L 149
 Felten, J.E., Morrison, P., 1966, ApJ, 146, 686
 Harris, D.E., Grindlay, J. E., 1979, MNRAS, 188, 25
 Harris, D.E., Carilli, C.L., Perley R.A., 1994, Nature, 367, 713
 Kaneda, H., Tashiro, M., Ikebe, Y., et al., 1995, ApJ, 453, L 13
 Laing, R.A., Riley, J.M., Longair, M.S., 1983, MNRAS, 204, 151
 Pacholczyk, A.G., 1970, Radio Astrophysics, Freeman Eds., San Francisco
 Perley, R.A., Bridle, A.H., Willis, A.G., Fomalont, E.B., 1980, AJ, 85, 499
 Sambruna, R.M., Maraschi, L., Tavecchio, F., et al., 2002, ApJ in press; astro-ph/0201412
 Tashiro, M., Kaneda, H., Makishima, K., et al., 1998, ApJ, 499, 713
 Tashiro, M., Makishima, K., Kaneda, H., 2000, AdSpR, 25, 751
 Tashiro, M., Makishima, K., Iyomoto, N., Isobe, N., Kaneda, H., 2001, ApJ, 546, L 19
 Taylor, G.L., Dunlop, J.S., Hughes, D.H., Robson, E.I., 1996, MNRAS, 283, 930
 Vikhlinin, A., 2001, http://cxc.harvard.edu/cal/Links/Acis/acis/Cal_p rods/vfbkgrnd/index.html